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Bottom-up guidance to grouped items in conjunction search: Evidence for color grouping

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ABSTRACT

Previous studies have demonstrated that observers can search through a subset of items carrying a minority feature to find a conjunction target (Sobel & Cave, 2002). We examined whether subset search takes place when participants have less specific foreknowledge of the target (when the target is one of two possible items), measuring eye movements as well as reaction times. When there were unequal ratios of distractors, fixations were initially directed to the small subset. These initial eye movements were often directed between items with the same feature, suggesting guidance from pooled feature values. There was stronger guidance within color- than orientation-defined groups, although the features were balanced for salience. The results suggest that grouping of items by color operates more globally than grouping in orientation.

1. Introduction

In everyday life, the way we search for objects in the environment is affected both by the nature of the items present and how the stimuli are related to what we are looking for. For example, when looking for your friend in a crowd, your eye might be drawn to people similar in height and hair color. Experimentally, the processes behind such real-life examples has been investigated using visual search, where participants look for a target randomly placed amongst an array of distractors varying in number and form. A number of studies have investigated how the physical nature of the search items (bottom-up factors) affect behavior (see Müller & Krummenacher, 2006, and Wolfe, 1998, for reviews), and how these effects are modulated by the top-down knowledge the target (e.g., Eimer & Kiss, 2008; Wolfe et al., 2004). Effects of top-down guidance have been examined both when search is efficient and when it is inefficient (e.g., with complex displays), while effects of bottom-up guidance have primarily been studied when search is efficient (see Müller & Krummenacher, 2006). Little research has been conducted on bottom-up search when performance is inefficient (e.g., when the target is defined by a conjunction of features). The current study requires participants to detect one of two possible conjunction targets, thereby reducing target-specific top-down biases (cf. Linnell & Humphreys, 2007) while manipulating bottom-up featural relationships between distractors. The experiment demonstrates how these bottom-up relationships can modulate search of complex displays, and whether these effects differ as a function of the stimulus dimensions used to guide search.

Search for a conjunction of features is typically dependent on the number of stimuli in the display (see Wolfe, 1998). Several studies have also shown that the relative number of each type of distractor influences behavior. Search is more efficient when the target falls within the smaller of two groups of distractors than when the ratio is balanced (Bacon & Egeth, 1997; Egeth, Virzi, & Garbart, 1984; Kaptein, Theeuwes, & Van der Heijden, 1995; Sobel & Cave, 2002). Eye movement data also indicate that initial fixations are directed to items in the minority subset (e.g., Williams & Reingold, 2001). This pattern of 'subset search' has been interpreted to reflect bottom-up processes that direct search towards the smaller group of stimuli sharing a feature with the target (Sobel & Cave, 2002). Within the framework of models such as Guided Search Theory (GST: Wolfe, 1994; Wolfe, Cave, & Franzel, 1989, for details of the model), search may be guided to targets in the smaller subset of distractors because they possess higher salience than targets in the larger subset.

Alongside any stimulus-driven biases to the minority group, top-down knowledge of the likely target can also affect search (cf. Sobel & Cave, 2002). Kim and Cave (1995, 1999) used a probe dot methodology to measure the deployment of attention during conjunction search. Probes were detected quicker when positioned at the location of distractors sharing a feature with the target compared to when probes fell adjacent to distractors with no relation to the target. Search models accommodate such results by positing that top-down knowledge activates target features, increasing the likelihood that distractors carrying those features are selected

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(Heinke & Backhaus, 2011; Mavritsaki et al., 2011; Wolfe, 1994). This top-down bias to target features may combine with bottom-up saliency signals to optimize search to distractors in the minority set with the appropriate feature values.

One way to reduce the effects of top-down bias in search is to increase the number of targets that have to be detected. Consistent with this, search for one of two possible targets is typically less efficient that search for one possible target even with the same items are present in the field (Menneer et al., 2007, 2010). The present study adopted this approach to reducing top-down biasing effects, and then examined the way in which bottom-up variation in subsets of distractors modulated performance. Does minority-set guidance occur when top-down effects decrease?

We also evaluated if guidance from items sharing their color with the target was different to guidance from items sharing their orientation. Several studies have shown that, during a conjunction search, search is more likely to be guided to distractors sharing their color rather than their orientation with the target. Williams and Reingold (2001), for example, measured eye movements as participants searched for targets defined by a triple-conjunction and varied the discriminability of the stimuli along each dimension. Targets shared one feature with each type of distractor and were a conjunction of color, orientation and shape. Fixations were more likely to land on distractors with the same color as the target compared to those sharing either of the other two dimensions. A similar color bias was evident on search for targets balanced for search efficiency within the two defining dimensions (Hannus et al., 2006). By adopting a two-target methodology here (where participants do not know which of two targets could appear on a trial) we investigated whether there is a dimensional bias when prior knowledge of target identity was reduced.

In addition to measuring behavioral performance using reaction times and errors, we also assessed eye movements to provide a finer-grained analysis of the microgenesis of search. Several studies (e.g., Findlay & Gilchrist, 1997; Zelinsky et al., 1997) have demonstrated that, during visual search, initial eye movements can be directed between, as well as to, individual items. Zelinsky et al., in particular, demonstrated that first saccades were towards central positions between stimuli (the 'center of gravity' of the items) while subsequent fixations were more accurately directed towards individual items. Zelinsky et al. suggested that the initial between-item fixations were due to search items being first processed in parallel, with eye movements directed towards a representation in which multiple rather than individual items are coded. The findings indicated that the multiple-item representation was decomposed over time, so that second eye movements are made to more detailed representations of individual stimuli.

We evaluated changes in the patterning of first and second fixations when participants were presented with balanced and unbalanced (majority/minority) sets of distractors. Shen, Reingold, and Pomplun (2000) assessed eye movements in subset search task and found that eye movements were guided towards subsets of stimuli: defined by color and shape. Here we examined whether there was differential accuracy of eye movements made into majority and minority featural sets. For example, consider an account in terms of Guided Search Theory (Wolfe, 1994) in which attention is guided to activation profiles at which locations receive summed activity from separate feature maps. Due to lateral inhibition, the bottom-up contribution of each item depends upon the number of local items sharing an attribute with the target. The smaller the number, the greater the input of this feature to the activation map. Therefore, the activation profiles should be higher and sharper for minority relative to majority feature sets, as the minority items will (on average) be spaced further apart, having fewer stimuli within their map. The lower and shallower profile for the majority items should result in greater pooling of their features and less precise guidance within the map. Thus fixations to stimuli in the majority group should be less accurately targeted at individual stimuli and more likely to fall in empty regions of space.

1.1. The current study

Performance was evaluated in a conjunction search task with two possible targets, to maximize effects of bottom-up relative to top-down guidance of search. Eye movement, reaction times (RTs) and errors were measured for targets defined in terms of particular combinations of color and orientation. Prior to the main experiment, we ran control studies to ensure that target features were balanced for salience across the two dimensions (for details of these studies see Anderson, Heinke, & Humphreys, 2010), so that dimension-specific biases between color-and orientation-defined subsets were minimized (see Williams & Reingold, 2001). There were three conditions in which we varied the ratios of different types of distractors; there were: (i) minority color/majority orientation groups, (ii) equally distributed color-orientation groups and (iii) majority color/minority orientation groups. We assessed first and second fixations during search to evaluate not only where search was initially directed, but also whether it dwelled or shifted from one feature set following the first fixation.

2. Method

2.1. Participants

Thirty-nine University of Birmingham students, eight male, 31 female, aged 18–30 (average 20.47) took part. All had self-reported normal or corrected-to-normal vision; normal color perception, assessed using *Ishihara's Tests for Color-Deficiency* (Ishihara, 1981); and were naïve as to the purpose of the experiment.

2.2. Design

There were two main independent variables manipulated within subjects: display type (minority color/majority orientation, equal distribution, majority color/minority orientation, see Section 2.5) and target type (green horizontal, blue vertical).

2.3. Apparatus

The stimuli were presented on a display PC with a 22-in. color CRT monitor (ViewSonic P225f, 2004). The stimuli were generated by an E-Prime program (Schneider, Eschman, & Zuccolotto, 2002) at a screen resolution of 640×480 that recorded RTs and accuracy via a standard UK keyboard. Audio feedback was provided by stereo Genius speakers. Participants placed their head on a chin rest .6 m from the screen, in a dimly lit room with windows blacked-out to avoid luminance changes. The chin rest and monitor heights were adjusted for each participant so eye gaze was central to the display screen. Eye movements were recorded using an SMI infra-red Remote Eyetracking Device III (SMI RedIII; SensoMotoric Instruments GmbH, Germany 2002–2004). The gaze position accuracy was $.5^\circ$, with sampling rate 50 Hz. The eye-tracking camera was linked to a separate PC to the one displaying the search stimuli. IViewX (version 1.07.00) software was used to calibrate the camera and collect data. E-Prime software on the display PC was synchronized via an Ethernet cable with the IViewX software.

2.4. Stimuli

All the stimuli were presented on a grey background. The fixation circle was .6 cm diameter (visual angle of $.57^\circ$ at .6 m viewing distance). For each trial there were two possible targets, either a blue horizontal or green vertical bar, with two types of distractor present: blue vertical and green horizontal bars. The dimensions of the bars were 1 cm (1°) long by .3 cm (.3°) wide. Grey symbols, '+'s or '×'s, were equally distributed across all stimuli. Color levels are shown in Table 1. Anderson, Heinke, and Humphreys (2010) reported that the color- and orientation-defined targets were searched equally efficiently in single feature search tasks where the target could be defined along each dimension.

2.5. Procedure

Participants were informed of the nature of two possible targets prior to the experiment and they were also told that either target was equally likely on each trial. Visual reminders of the targets were also presented adjacent to the computer monitor but only during the practice phase, when eye movements and behavioral data were not recorded. On each trial, a fixation circle was presented first for 1000 ms, before a 100 ms inter-stimulus interval (ISI) which was followed by an array of stimuli with one target and eight distractors. These nine bars were presented randomly within a central invisible circle of diameter 10 cm (9.5°) with 12 possible positions, staggered to lessen spatial interactions between distractor stimuli. The ratio of the two distractor types was manipulated as follows: two blue vertical bars and six green horizontal bars (2BV, 6GH); 4GV, 4GH; and 6BV, 2GH (see Fig. 1 for examples). The target was either a blue horizontal (50%) or green vertical bar and both the distractor ratio and target varied randomly trial-on-trial.

Participants were asked to indicate whether there was either an × or '+' symbol on the search target by pressing either '*Z*' or '*M*' on the computer keyboard. The key assignment was reversed for half the participants. There were between nine and 16 practice trials followed by a block of 72 experimental trials. Feedback was provided as follows. If the response was correct, participants heard a medium pitched sound and the word 'Correct' was displayed. If incorrect, a lower note was played and the word 'Incorrect' was displayed instead. The time until participants' response was recorded (RTs), with the accuracy of the response also noted. The positions of eye movements were also recorded during the search task.

3. Results

To maximize the number of trials per condition the data were pooled across target type. Ratios were then coded according to the size of the distractor group sharing its color or orientation with the target. As the two dimensions co-varied, the resulting display types were: (i) minority color/majority orientation, (ii) equal distributions, (iii) majority color/minority orientation. This meant, for example, a trial with a blue horizontal target and two blue vertical and six green horizontal distractors (2BV and 6GH) was coded as belonging to the minority color/majority orientation condition. The same coding was used when the green vertical target was surrounded by a distractor ratio of 6BV, 2GH (see Fig. 1).

Table 1
Color levels used for the stimuli. Hue, saturation and luminance levels were adjusted using the Microsoft Paint computer program. Independent photometer readings were taken with a Salford Electrical Instruments Exposure Photometer.

Color	Hue	Saturation	Luminance	Photometer reading (cd m^{-2})
Blue	140	40	120	12.16
Green	80	40	120	12.16
Grey	160	0	200	34.26
White	160	0	240	143.13
Black	160	0	0	6.02

3.1. RTs

RTs were used as an overall measure of search efficiency. Prior studies with fixed target-identities across trials have shown more efficient search when the target matched the minority color or minority orientation subset of distractors compared to displays with balanced ratios of distractors (a 'ratio effect', Sobel & Cave, 2002). If the ratio effect occurs even when participants do not have exact fore-knowledge of the target, we would expect a similar facilitation for detecting targets in the minority group here.

Several participants required breaks in the middle of the block of trials. For all analyses, these trials were discarded (RTs > 5000 ms). Less than 1% of data were removed as a consequence. To control the family-wise error rate, all *post hoc* pair-wise comparisons included Bonferroni adjustments and were measured as significant at the $p < .05$ level. Three participants were removed due to accuracy of less than 90%. Trials that were inaccurate were removed and median RTs in each condition for each participant were calculated.

Group means are shown in Fig. 2. A one-factor ANOVA (display type) revealed a borderline significant main effect of display type ($F(2, 70) = 2.9$, $p = .057$, partial $\eta^2 = .079$). RTs were significantly shorter in the minority color/majority orientation condition compared to the equal condition (difference of 119 ms, $p = .015$). There was a trend towards a similar facilitation effect for the majority color/minority orientation condition (difference of 76 ms, $p = .115$). There was no difference in RTs between the two minority/majority display types (difference of 43 ms, $p = .432$).

3.2. Accuracy

There was no speed-accuracy trade-off. The mean accuracy data are shown in Table 2.

The data indicate that search for two possible targets was facilitated when the target shared a feature with a minority of distractors, suggesting that conjunction search can operate via smaller subsets even when top-down, target-driven guidance is reduced (c.f., Sobel & Cave, 2002). There was also a trend towards greater facilitation when the minority of distractors matched the target color compared to when the minority subset matched the target orientation. This suggests a marginal advantage towards selecting items with the same color as the target. This was explored further in the analysis of the eye movements.

3.3. Eye movements

To give a more detailed indication of search, for each trial eye movements were recorded from the onset of the search array until response. A fixation was classified when the speed of the eye movement remained below 50 visual degrees per second (°/s) for 100 ms. Data recorded during eye-blinks and off-screen eye movements were discarded, as were fixations detected within 80 ms of array onset (see van Zoest, Donk, & Theeuwes, 2004). The number of fixations per trial varied depending on search efficiency. However, at least 80% of the trials from each participant contained two fixations or more. Only the first two fixations were analyzed, therefore, with trials with fewer fixations removed. Data from three participants were eliminated due to reduced response accuracy (see RT analysis) and a further participant was removed due to technical issues calibrating the eye tracker.

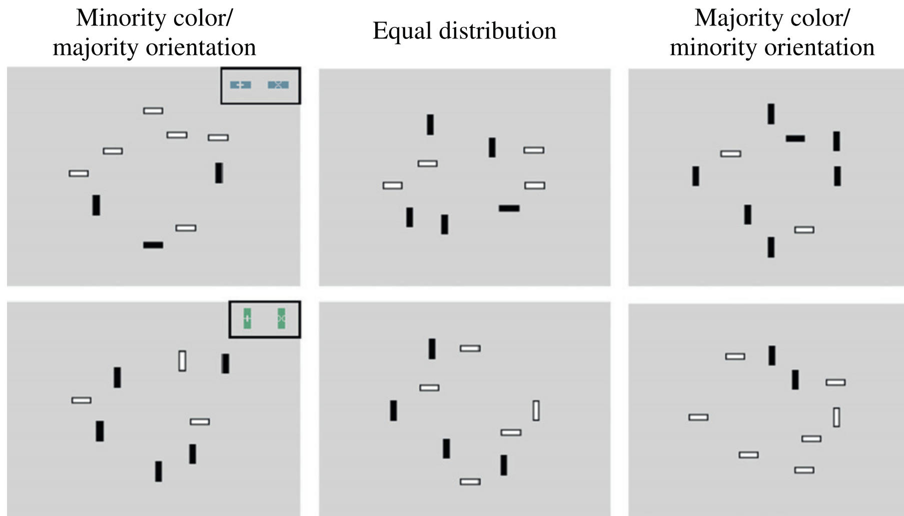

Fig. 1. Illustration of types of display. Distractor ratios varied from two blue vertical and six green horizontal distractors (2BV and 6GH) to 4BV, 4GH to 6BV, 2GH. Displays were coded according to the size of the group of distractors (minority or majority) having the same color/orientation as the target. The top series of displays offer examples item configurations with blue horizontal targets; the bottom series show displays with green vertical targets. For clarity, blue stimuli are presented in black and green stimuli in white, while the light grey + and × symbols places on all items are not shown. Examples of actual targets are shown in inset boxes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

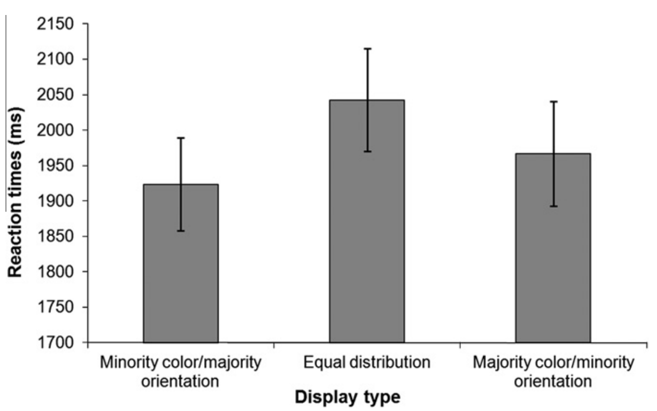

Fig. 2. Mean (±one standard error) of median RTs from Experiment 1, divided by display type. The ratio was coded to indicate the size of the distractor group sharing its color/orientation with the target (see Fig. 1).

Table 2
Mean percentage of correct responses by display type (see Fig. 1).

Display type	Percent correct
Minority color/majority orientation	95
Equal distribution	97
Majority color/minority orientation	96

3.3.1. Frequency of fixating the nearest item

On each trial, Euclidean distances between fixations and all the items were calculated and we identified the nature of the item closest to each fixation. The mean frequency of each participant fixating on each type of stimulus was then calculated (target, a color-related or an orientation-related distractor) and then normalized by the number of trials where there were two fixations to that display type. The frequencies were adjusted for chance, so that the probability of a random fixation directed to each item was subtracted from the relevant frequencies at both fixations. For fixations nearest to a target, this value was $^{1}/_{9}$ (there were nine search items). For fixations nearest to distractors, the value depended on the display type and the number of distractors with the same feature. For example, for fixations nearest to distractors with the target color, the value would be $^{2}/_{9}$ on trials to minority color/majority orientation displays (two distractors with the same color as the target were present), $^{4}/_{9}$ on trails with equally distributed displays, and $^{6}/_{9}$ on trials with the majority color/minority orientation displays (six distractors with the same color as the target were present). As a consequence, a measured frequency of zero indicated that the likelihood of a fixation directed to that item was no different from chance. Positive values indicate that there were more fixations to the item than chance, while negative values indicate that fixations to the item were lower than chance. Group means of these adjusted frequencies are shown in Fig. 3.

As the frequency of fixating different items co-varied (on a trial, if participants fixated the target they would not be looking at either type of distractor), it is not feasible to directly compare fixation number across item type (target, distractor with target color, distractor with target orientation). Initially, fixations nearest to targets were analyzed, with an increase in this frequency correlating to a decrease in distractor-fixations.

3.3.1.1. Frequency of fixating the target. Improved search efficiency on displays with a minority distractor subset matching the target should be reflected in an increased number of fixations to the target, relative to displays with even distractor ratios. A two-factor ANOVA (fixation number, display type) revealed a main effect of fixation number ($F(1,34) = 71.1$, $p < .001$, partial $\eta^2 = .67$), with the number of eye movements to the target increasing from fixation 1 (adjusted frequency of .041) to fixation 2 (adjusted frequency of .179). There was also a main effect of display type ($F(2,68) = 7.6$, $p = .001$, partial $\eta^2 = .183$). *A priori* comparisons across display type indicated a reduced likelihood of target-fixations when the distractor ratio was balanced compared to when both the minority orientation subset and the minority color subset of distractors matched the target (adjusted probability differences of .063 and .038, $p < .001$ and $p = .038$, respectively). The findings suggest, in agreement with the RT data, that the efficiency with which the target is selected increases on displays with uneven distractor ratios.

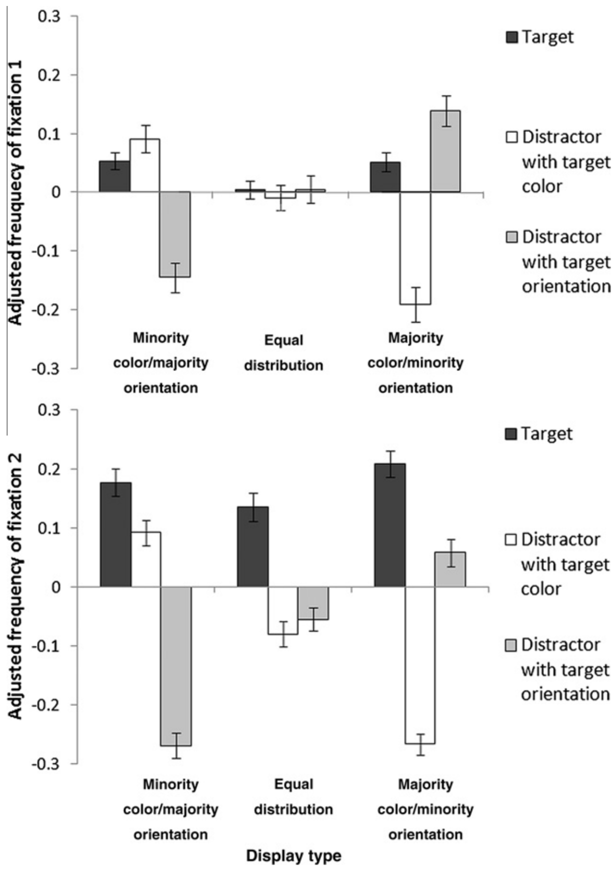

Fig. 3. Means (±one standard error) of mean frequency of fixations nearest to the target, or distractors with the target color or target orientation. The data are adjusted for chance split by display type (see Fig. 1) and fixation number.

3.3.1.2. Frequency of fixating a distractor type. To investigate how eye movements are guided to the target, the number of fixations nearest to distractors matching the target in color or orientation were then analyzed. If increased target-fixations (and shorter RTs) on displays with uneven distractor ratios were directed by minority subsets sharing a feature with the target (Sobel & Cave, 2002), then increased fixations to distractors in these subsets would be expected (cf. Shen et al., 2000). A two-factor ANOVA (fixation number, display type) indicated main effects of fixation number ($F(1,34) = 77.178$, $p < .001$, partial $\eta^2 = .694$) and display type ($F(2,68) = 7.578$, $p = .001$, partial $\eta^2 = .182$). Fixations towards both types of distractors reduced at fixation 2 (adjusted frequency of $-.083$) compared to fixation 1 (adjusted frequency of $-.018$), while there were fewer fixations to distractors on displays with unbalanced compared with balanced ratios (differences of .023, $p = .037$; and .03, $p = .002$, for minority color and orientation displays, respectively). There was also a distractor type $\times$ display type interaction ($F(2,68) = 85.496$, $p < .001$, partial $\eta^2 = .715$). When the minority subset matched the target color, more fixations were directed towards distractors with the target color compared to distractors with the target orientation (a difference of .298, $p < .001$). When the minority subset matched the target orientation, there was a similar bias but towards distractors with the target orientation relative to the target color (a difference of .327, $p < .001$).

These findings indicate a bias towards target features in minority groups on displays with uneven ratios. When the relative magnitudes of the biases to minority color and orientation subsets were assessed, there were no main effects or interactions (all $ps > .2$). This indicates that the salience of the minority subset defined by color or orientation was matched and can be seen as confirmation of the measures taken in advance to adjust efficiency of color and orientation search (see Anderson, Heinke, & Humphreys, 2010).

3.3.1.3. Frequency of fixating the target vs. the minority distractor subset. We next compared the salience of the target with that of the minority distractor subset on a particular display, indexed by the eye movement data. A three-factor ANOVA was conducted with the factors being item type (target, distractor), display type (minority color or orientation set matching the target) and fixation number (first or second). There was a reliable main effect of fixation number ($F(1,34) = 19.671$, $p < .001$, partial $\eta^2 = .367$). There were fewer first fixations to targets and minority group of distractors than second fixations (adjusted frequencies of .083 vs. .134). There was also a fixation number $\times$ item type interaction ($F(1,34) = 18.635$, $p < .001$, partial $\eta^2 = .354$). Initial fixations were more likely to be to the smaller subset of distractors than the target (a difference of .062, $p = .017$), while there were more second fixations to the target than to the minority subset of distractors (a difference of .118, $p = .001$).

There was also a borderline significant three-way interaction ($F(1,34) = 3.853$, $p = .058$, $\eta^2 = .102$), suggesting that the fixation number $\times$ item type interaction varied with display type. When the target color matched the minority subset, there was no difference between the number of first fixations to the target or the minority subset of distractors (a difference of .037, $p = .235$). In contrast, more second fixations were to the target compared to the distractor subset (a difference of .087, $p = .008$). However, when the target orientation matched the minority subset, more initial fixations were directed to the distractor subset than the target (majority color/minority orientation, a difference .086, $p = .039$); the opposite bias was evident at second fixation (a difference of .151, $p = .001$).

The above findings suggest differential patterns of behavior depending on the feature shared by the minority distractor group and the target. When the target matched the minority group in color, initial eye movements were directed equally to either the target or the minority distractors, with subsequent eye movements guided towards the target. When the target matched the minority subset in orientation, more initial eye movements were to the small distractor subset than the target, with second fixations then directed to the target.

3.3.2. Target-fixation distance

To examine the progress of search from first to second fixation, we assessed the accuracy of fixations to targets as a function of the closest distractors to the first fixation. Search of the small subset on uneven display trials (Sobel & Cave, 2002) would be indicated by more accurate second fixations to the target following initial eye movements to the minority of distractors matching the target. The Euclidean distances of the first two fixations to the target were calculated, with this measure analyzed as a function of the fixation number, the identity of the nearest item to fixation 1 (target, distractor carrying the target color, distractor carrying the target orientation) and display type. The group means of distances from the target are shown in Fig. 4. For reference, the furthest a distractor could be from the target was 10.8° while the minimum was 2.6°. Performance was assessed separately according to whether fixation 1 fell nearest a target or a distractor.

3.3.2.1. Fixation 1 nearest the target. A two-factor ANOVA (display type $\times$ fixation number) demonstrated a main effect of fixation number ($F(1,34) = 178.83$, $p < .001$, partial $\eta^2 = .84$). First fixations were closer to the target than second fixations (1.2° vs. 3.5°). No other main effects or interactions reached significance ($Fs < 1$). The findings suggest that initial fixations to the target that did

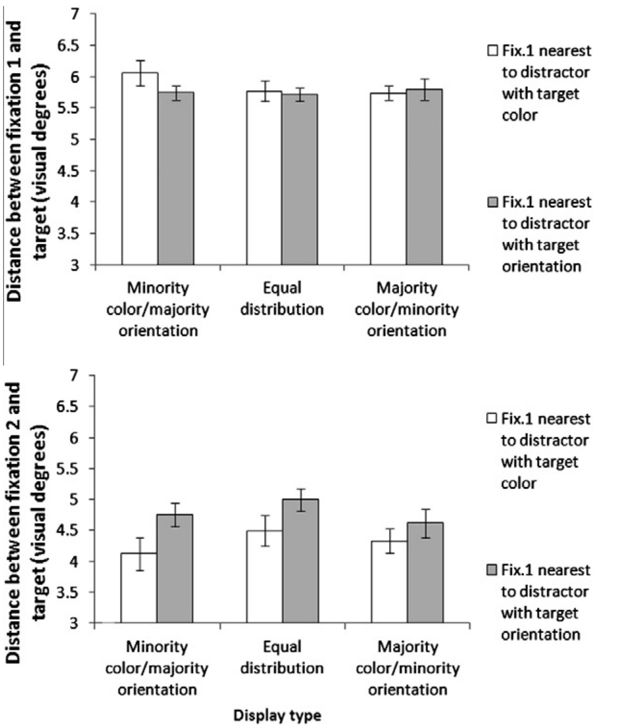

Fig. 4. Mean distances between fixation and target (±one standard error) in degrees of visual angle. Data are separated according to the nearest distractor to fixation 1, display type and fixation number.

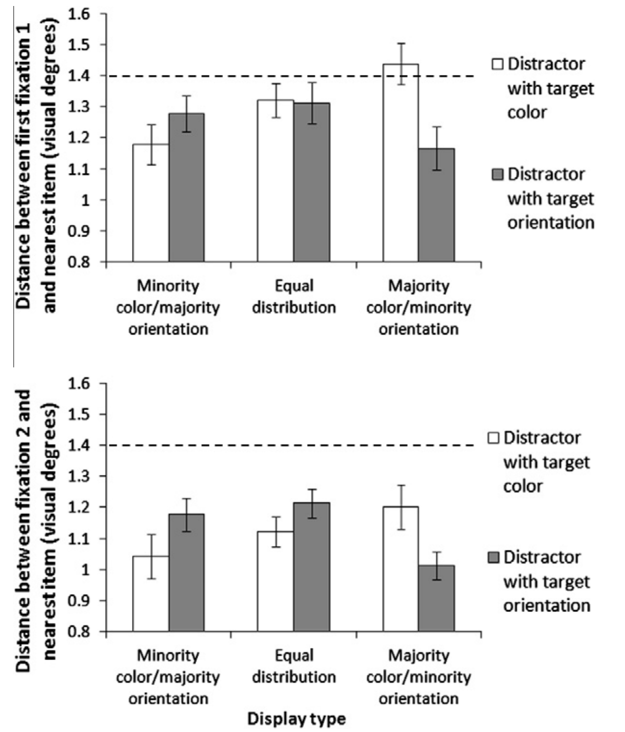

Fig. 5. Mean distances between fixations and the nearest item (±one standard error) in degree of visual angle, with only fixations adjacent to distractors included. Data are separated by type of nearest distractor, display type and fixation number. The mean distance between the midpoint of two adjacent stimuli (1.4°) is displayed for reference.

not trigger a response (all trials analyzed included at least two fixations) led to less accurate subsequent fixations.

3.3.2.2. Fixation 1 nearest to a distractor (see Fig. 4). A three-factor ANOVA (display type × fixation number × distractor type) revealed a main effect of fixation number ($F(1,34) = 97.419$, $p < .001$, partial $\eta^2 = .741$). In contrast to when the first fixation was already near the target, the distance to the target decreased across fixations (5.8° vs. 4.6°). There was also a fixation number × distractor type interaction ($F(1,34) = 7.51$, $p = .01$, partial $\eta^2 = .181$). While there was no difference across distractor types at fixation 1 (a difference of .107, $p = .358$), second fixations were closer to the target after first fixations were directed towards distractors with the same color as the target compared to when first fixations were towards distractors with the target's orientation (a difference of .472, $p = .019$). This pattern did not vary across display type (three-way interaction: $F(2,68) = 1.211$, $p = .304$, partial $\eta^2 = .34$). The findings are consistent with smaller group search occurring when the minority group of distractors matched the target's color, but not when the minority subset matched the target in orientation. The current results suggest that any initial preference towards fixating items with the target-color (see also Hannus et al., 2006; Williams, 1966) is not reliant on knowledge of the target-identity, but may be due to stimulus-driven factors such as grouping (e.g., Found & Müller, 1996; Geyer, Müller, & Krummenacher, 2006; Geyer, Shi, & Müller, 2010).

3.3.3. Distance to nearest item

Items nearest fixations may be processed in conjunction with other items (assessed as a group), indicated by eye movements directed between objects (Zelinsky et al., 1997). Euclidean distances between fixations and the nearest item on all trials were therefore calculated. The data were separated by whether the nearest item was the target, a distractor with the target color, or a distractor with the target orientation, as well as by display type and fixation number. Mean distances from distractors across participants are shown in Fig. 5 (for clarity, fixations adjacent to targets were omitted). As a benchmark, the average distance from the nearest item and the midpoint between adjacent stimuli was 1.4°.

A three-factor ANOVA (fixation number, display type, item type) revealed main effects of fixation number ($F(1,34) = 37.245$, $p < .001$, partial $\eta^2 = .523$) and item type ($F(2,68) = 3.282$, $p = .044$, partial $\eta^2 = .088$). There were also two interactions: display type × item type ($F(4136) = 7.035$, $p < .001$, partial $\eta^2 = .171$) and fixation number × item type ($F(1.679,57.09) = 4031$, $p = .029$, partial $\eta^2 = .109$). Unpacking the first interaction, in displays with minority distractors with the target orientation, fixations adjacent to distractors with the target color were further away from these items compared to fixations nearest to distractors with the target orientation (a difference of .23, $p < .001$) and fixations adjacent to the target (a difference of .202, $p < .001$). There were no differences across item type on trials with other display types (*ps* > .1). The fixation number × item type interaction demonstrated little difference between fixation-item distances at fixation 1 (*ps* > .2). At fixation 2, however, distances from fixation to target were significantly reduced compared to distances to each type of distractor (target vs. distractors with the target color, difference of .109, $p = .047$; target vs. distractors with the target orientation, difference of .122, $p = .024$).

3.3.3.1. Distance from items in minority vs. majority subsets. Fig. 5 suggests that fixations to distractors matching the minority subset were more accurate than fixations to distractors in the majority subset. A three-factor ANOVA (group size, group dimension, fixation number) compared the distance of fixations from distractors in the minority group with those in the majority group. There were main effects fixation number ($F(1,34) = 18.578$, $p < .001$, partial

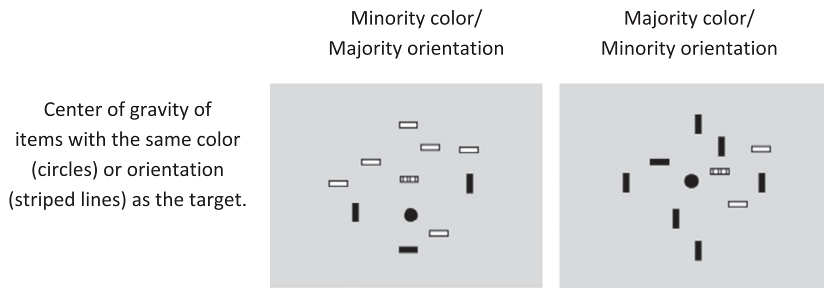

Fig. 6. Example displays with a blue horizontal target (a green vertical target could also be presented), with markers added to indicate the center of gravity of items carrying the color or orientation of the target. To allow distinction between search items, blue stimuli are presented in black and green stimuli in white, while for clarity the response-specific + and × symbols are not shown.

$\eta^2 = .353$) and group size ($F(1,34) = 17.08$, $p < .001$), partial $\eta^2 = .334$) and no interactions. Fixations were nearer to items on the second compared to first fixations (distances of 1.109° vs. 1.265°), while fixation distances to the nearest distractor were shorter when distractors were in the minority compared to the majority subset (1.1° vs. 1.273°). This is consistent with search being directed to groups of items rather than individual stimuli.

3.3.4. Distance to center of gravity of featural group

As a further assessment of search being directed to groups of items, we evaluated where fixations fell in relation to the center of gravity of groups of items (Zelinsky et al., 1997). On displays with unbalanced sets of distractors, the positions of the centers of gravity varied across the minority and majority color and orientation sets (*ps* < .001 for all comparisons; see Fig. 6 for examples). We classified first fixations according to the nearest neighbor and used this to categorize which group was the target of the fixation, measuring the distance from the fixation to the center of gravity of the group. Means across participants are shown in Fig. 7.

A repeated measures ANOVA was undertaken with three factors: fixation number (fixation 1 or 2), group size (minority or majority), and group type (target color or target orientation). The analysis revealed main effects of fixation number ($F(1,34) = 16.096$, $p < .001$, partial $\eta^2 = .321$), group size ($F(1,34) = 39.039$, $p < .001$, partial $\eta^2 = .534$) and group type ($F(1,34) = 8.26$, $p = .007$, partial $\eta^2 = .195$). First fixations were closer to the center of gravity of items matching the target compared with second fixations (distances of 3.5 and 3.9, respectively). Fixations were more accurate to the center of gravity of minority compared to majority sets (distances of 3.4° and 4°, respectively); and more accurate to groups with the target color compared to the target orientation (distances of 3.6° and 3.8°, respectively). There was also a group size × group type interaction ($F(1,34) = 19.842$, $p < .001$, partial $\eta^2 = .369$) and a three-way interaction ($F(1,34) = 6.702$, $p = .014$, partial $\eta^2 = .165$). To unpack the latter interaction, data from first and second fixations were analyzed separately.

3.3.4.1. First fixations. There were main effects of group size ($F(1,34) = 32.023$, $p < .001$, partial $\eta^2 = .485$) and group type ($F(1,34) = 9.804$, $p = .004$, partial $\eta^2 = .224$). There was also an interaction, ($F(1,34) = 19.676$, $p < .001$, partial $\eta^2 = .367$). First fixations to majority groups carrying the target orientation were less accurate to the center of gravity than to all the other groups (vs. minority orientation set, a difference of 1.13, $p < .001$; vs. majority color set, a difference of .916, $p < .001$). Fixations to minority and majority color groups also did not differ in accuracy relative to each groups' center (a difference of .034, $p = .818$).

3.3.4.2. Second fixations. At fixation 2, there was only a main effect of group size ($F(1,34) = 1.877$, $p < .001$, partial $\eta^2 = .357$). There was no difference in accuracy to minority color- and orientation-defined groups (a difference of .012, $p = .943$), but both were more accurate than to majority color and orientation groups (averaged distance for minority groups, 3.6°, and for majority groups, 4.2°). Interestingly, second fixations to majority color groups were less accurate that first fixations ($t(34) = 6.696$, $p < .001$, two-tailed). These data indicate initial fixations to color-defined groups are equally accurate across different group sizes. However, if attention went to the minority color group, then the fixation tended to remain in that set. Alternatively, if it went to the majority color group, then it tended to switch to the minority orientation set.

3.4. Eye movement latencies

The above data indicate that certain fixations were made to the space adjacent to search items. These inaccurate fixations may be made earlier after the onset of the display than more accurate fixations (reflecting a speed-accuracy trade-off). Analysis of the

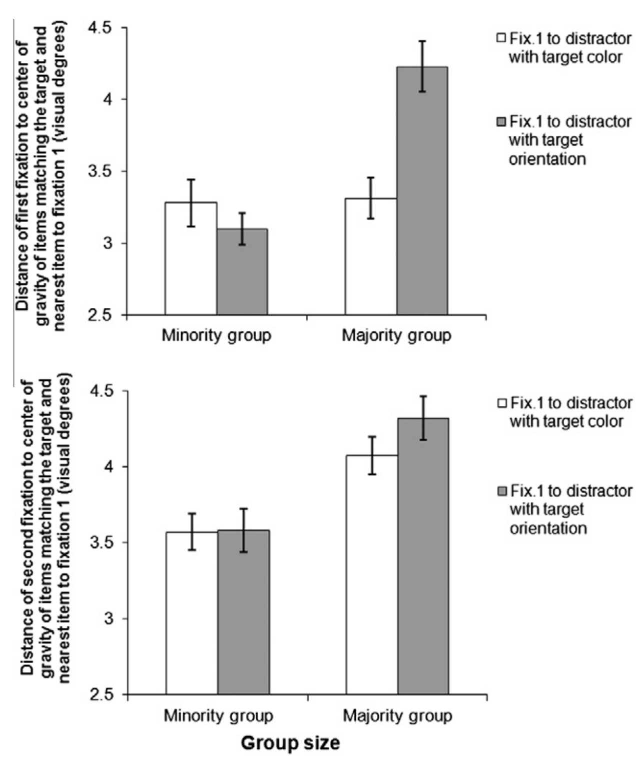

Fig. 7. Mean distance (±one standard error) of fixations to the center of the group with the same color or orientation as the items nearest to fixation 1. Data were split by group size and group type, categorized by the type of distractor adjacent to fixation 1 (e.g., target color or orientation).

median time from display onset until fixation onset (eye movement latencies), separated by display type and fixation number, indicated a main effect of fixation number ($F(1,34) = 286.399$, $p < 0.001$, partial $\eta^2 = .894$). Initial eye movements started earlier than second eye movements (280 ms vs. 620 ms, respectively). There was no variation in latencies across the display types, however (main effect, $F < 1$) and no interactions (display type $\times$ fixation number, $F < 1$). The data indicate that there was no trade-off between search speed and accuracy.

4. Discussion

We examined search for two possible conjunction targets of color and orientation as the ratios of distractors varied (with minority color or orientation sets carrying the target features). Search was overall more efficient for displays with uneven than evenly distributed sets of distractors. Given that top-down guidance to a specific target should be reduced here, data indicate that efficient subset search can be based on bottom-up guidance.

We also analyzed eye movements. Eye movements were biased towards items carrying the target features and towards items in the minority subset of distractors. The subset effects were relatively matched for color- and orientation-defined groups, though we will return to discuss if this reflects equal salience of color and orientation. Interesting differences did emerge between the color- and orientation-defined groups. For example, for color-defined groups, first fixations tended to go equally to the center of the minority and majority color groups. Also, first fixations were as close to the center of the minority orientation-defined group, but in all cases these were closer than to the center of the majority orientation-defined group. These data suggest that first fixations were directed on the basis of information pooled across the groups. For color, this pooled information is equally accurate across minority and majority groups. For orientation-defined groups, the pooling only appeared to operate for minority sets. For example, perhaps attention is directed to orientation-defined stimuli based on disparity signals computed only for a limited set of items, whereas attention is directed to color groups from more global computations across a display. Interestingly, once the initial eye movement appeared to be made to a majority color group, the next eye movement tended to move away from the group's center. This may reflect either the second eye movement being more locally driven within the color group (towards a local stimulus and away from the center of gravity), or to the eye movement shifting from the majority color group to the minority orientation group. There were too few third fixations to enable a more detailed analysis to be undertaken.

There were also differences in target selection within the orientation- and color-defined groups. When the smaller group of distractors was the same color as the target, initial eye movements were as likely to be directed towards the target as the same-color distractors. In contrast, when the target orientation matched the minority of distractors, more first fixations were directed towards the distractors within this subset than the target. This asymmetry was extinguished at fixation 2. One account of this disparity is that initial eye movements into the small orientation groups are not based on the orientations of the group members but on their color (which also formed a minority set, but not one carrying the target's color). First fixations would then be more likely to fall on the minority color distractors (also members of the minority distractor set) than on the target, before second fixations are oriented to the target. According to this account, first fixations tended to be directly to color- rather than orientation-defined groups, despite the colors and orientations being matched for saliency in the initial pilot studies (see Anderson, Heinke, & Humphreys, 2010), and despite participants having to search for two targets. To provide a test of this proposal, we conducted an additional analysis in which first fixations classified as falling into the target-orientation minority group were measured for their distance in relation to the whole group and the distance between just the minority same-color distractors. The distance between fixation and the mid-point between the same color distractors was smaller than that between fixation and the center of gravity of the orientation minority group – consistent with fixations to the minority color distractors ($t(34) = 2.17$, $p = .037$, two-tailed).

We suggest that, even with salience differences overruled and top-down differences minimized, color remained dominant for the parsing of the displays (see Hannus et al., 2006). Search therefore progressed by group-based analysis of stimuli, rather than item-by-item. Previous studies have suggested that local items can be processed together (as clumps, see Pashler, 1987). The distance experiments here indicate equally accurate fixations to the center of large and small color groups – this is consistent with whole-display pooling of color and search is not just directed on the basis of local clusters of same-colored stimuli. Search may therefore be restricted to a color subset of items being processed together (following Egeth, Virzi, & Garbart, 1984; Found & Müller, 1996; Geyer, Müller, & Krummenacher, 2006; Geyer, Shi, & Müller, 2010), with the efficiency of this parsing determined by its difficulty and available processing capacity (Fisher, 1982; Fisher, 1984; Sung, 2008). It may therefore be that processing items with the same color presented less of a drain on resources relative to items with the same orientation.

5. Conclusions

Conjunction search was guided towards minority featural subsets matching the target when the target identity was unknown *a priori*. However, initial inspection involved the processing of items with the same color in parallel across the item array, even though item features (color and orientation) had been balanced for salience. Search then progressed with in the color-defined framework. We posit that featural grouping plays a major role in complex search, such as one for a conjunction of features.

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